

# Reaction plane angle dependence of dihadron azimuthal correlations from a multiphase transport model calculation

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Dihadron azimuthal angle correlations relative to the reaction plane have been investigated in Au + Au collisions at  $\sqrt{s_{NN}} = 200$  GeV using a multi-phase transport model (AMPT). Such reaction plane azimuthal angle dependent correlations can shed light on path-length effect of energy loss of high transverse momentum particles propagating through the hot dense medium. The correlations vary with the trigger particle azimuthal angle with respect to the reaction plane direction,  $\phi_s = \phi_T - \Psi_{EP}$ , which is consistent with the experimental observation by the STAR collaboration. The dihadron azimuthal angle correlation functions on the away side of the trigger particle present a distinct evolution from a single peak to a broad, possibly double peak, structure when the trigger particle direction goes from in-plane to out-of-plane of the reaction plane. The away-side angular correlation functions are asymmetric with respect to the back-to-back direction in some regions of  $\phi_s$ , which could provide insight on testing  $v_1$  method to reconstruct the reaction plane. In addition, both the root-mean-square width ( $W_{rms}$ ) of the away-side correlation distribution and the splitting parameter  $D$  between the away-side double peaks increase slightly with  $\phi_s$ , and the average transverse momentum of the away-side associated hadrons shows a strong  $\phi_s$  dependence. Our results indicate that strong parton cascade and resultant energy loss could play an important role for the appearance of a double-peak structure in the dihadron azimuthal angular correlation function on the away side of the trigger particle.

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## I. INTRODUCTION

Lattice QCD calculations predicted that a novel state of matter [1], distinct from ordinary hadronic matter, can be created in ultra-high energy heavy-ion collisions. The BNL Relativistic Heavy Ion Collider (RHIC) was constructed to investigate the properties of the new state of matter [2]. Studying the properties of this dense nuclear matter is a great challenge both experimentally and theoretically. Recently features of partonic collectivity and strongly interacting have been found for the matter of extreme temperature and energy density created in nucleus-nucleus collisions at RHIC [3–6]. The energy loss of hard partons traversing the dense medium created in the collisions is a crucial question. Usually, there are two main mechanisms causing a jet to lose energy: elastic collisions with deconfined partons and induced gluon radiation [7–13], and the gluon radiation is considered as the main process responsible for energy loss. Both mechanisms suggest that the energy loss would depend strongly on the traversed path length of the propagating jets [14–16]. Two particle azimuthal angular correlation has been demonstrated as a good probe to investigate the interactions between jets and the hot dense medium [17, 18]. It has been reported previously, at RHIC, that for a high  $p_T$  trigger particle, the correlated

yields at  $p_T > 2$  GeV/c on the away side are strongly suppressed [17], while for lower  $p_T$  the yields are enhanced. The correlated hadrons on the away-side appear to be partially equilibrated with the bulk medium and the azimuthal angular correlation distributions are much broader, possible with double peaks [20–22]. Recently many theoretical models have been proposed to describe the phenomenon: Mach-cone shock waves generated by large energy deposition in the medium [23], conical emission due to Cherenkov radiation [24], the excitation of collective plasmon waves [25], large angle gluon radiation [26, 27], strong parton cascade [28–30], jets deflected by radial flow [25, 31] and path-length dependent energy loss [32]. It has also been observed previously that the double peak structure in the dihadron angular correlation strongly depends on  $\phi_s$ , the trigger particle azimuthal angle with respect to the direction of the event plane [33, 34]. The angular correlation distributions on the away side are different between in-plane and out-of-plane orientations which indicate a strong path-length effect on parton-medium interactions [34]. However, no Monte Carlo simulation has been performed to demonstrate such kind of reaction plane angle dependence so far. In this work, we will use a multi-phase transport model (AMPT) [35] to reveal the dependence of the reaction plane orientation on the dihadron correlation structure which can be understood by the path-length effect of large elastic partonic energy loss.

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AMPT model is a hybrid model which consists of four main components: the initial conditions, partonic inter-

actions, the conversion from partonic matter to hadronic matter and hadronic rescattering. AMPT model includes two versions: the default version and the string melting version where strings are melted and hadronizations using parton recombination mechanism. Previous studies have shown that the partonic effect could not be neglected and the string melting AMPT model which contains stronger parton cascade is much more appropriate than the default AMPT model when the energy density is much higher than the critical density for the predicted phase transition [35–37]. The parton cascade model ZPC in the AMPT model only includes elastic  $2 \rightarrow 2$  partonic interactions [35], higher order inelastic process, which might become dominant at high densities during the early stage of relativistic heavy ion collisions [38], have not been included. To fully model the parton energy loss, in addition to the elastic energy loss the radiation energy loss (many-body inelastic interactions in general) [10, 11] should also be implemented in this hybrid transport model. However, it is not the intention of our current work to embark on such a comprehensive task of implementing radiation energy loss in AMPT. In order to match the parton energy loss in experimental data a large elastic scattering cross section ( $\sigma$ ) of 10 mb has to be used in AMPT model. The large elastic cross section could contribute to the emergence of a double peak structure on the away side angular correlation distribution.

For mid-central collisions, the initial overlap region of the two nuclei looks like an almond, Figure 1 shows the initial parton coordinate distribution for 40% collision centrality from AMPT model simulations. The dimensions of dense matter distribution for in-plane and out-of-plane are quite different in mid-central collisions. We have calculated the eccentricity of the initial state, right after the collision in AMPT model, to be around 0.15. Particles along out-of-plane will on average propagate a longer path length than those along the in-plane direction. Triggered high momentum particles are biased preferentially from the surface area and outward from different azimuthal angles. The corresponding away side jet and the associated particles will propagate through different dense medium length. This can result in different energy loss due to dependence on interaction strength between the traversing parton and the dense medium, which may lead to different correlation structures on the back-to-back direction.

## II. ANALYSIS METHOD

In order to investigate the path-length effect, we divide the whole initial angular phase space region into 16 equal slices based on  $\phi_s = \phi_T - \Psi_{EP}$  in Fig 2, where  $\phi_T$  and  $\Psi_{EP}$  are the azimuthal angle of triggered particle and event plane, respectively. We calculate the dihadron azimuthal angle correlations between a high  $p_T$  hadron (trigger hadron) and low  $p_T$  one (associated hadron) sep-

arately in each slice. The analysis method is similar to that used by the experiments [19, 39–41]. In the same event, pairs of an associated particle with a triggered particle are accumulated to obtain  $\Delta\phi = \phi_{assoc} - \phi_{trig}$  raw distributions, where  $\phi_{assoc}$  and  $\phi_{trig}$  are the azimuthal angle of associated particle and triggered particle, respectively. In order to reproduce the background which is mainly from the anisotropic flow [13, 15], a mixing-event method is applied. We mixed the events which have very close centrality into a new event, and extracted  $\Delta\phi$  distribution to be used as a background distribution. A zero yield at minimum (ZYAM) assumption was adopted to subtract the background [41]. We can directly use the event plane angle  $\Psi_{EP}$  in our AMPT model simulation which sets  $\Psi_{EP} = 0$ .

## III. RESULTS AND DISCUSSIONS

Figure 3 shows the dihadron correlation functions for 16 slices as determined by the trigger particle emission angle with respect to the reaction plane. The data are Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV from AMPT model simulation with a 20-60% collision centrality. We set  $p_T$  range for trigger particles to be  $2.5 < p_T^{trig} < 6$  GeV/c and for associated particles to be  $0.15 < p_T^{asso} < 3$  GeV/c in our analysis. Both triggered and associated particles are further selected with a pseudo-rapidity cut of  $|\eta| < 1$ . We can observe distinct evolutions from in-plane to out-of-plane on both near and away side. The near side correlations maintain a single Gaussian structure while the correlation yields decrease from in-plane to out-of-plane direction. On away-side, however, the correlation structure evolves from a single peak to double peaks. Furthermore, we note that the double peaks are not symmetric for data from some trigger particle emission directions. For further discussion on the asymmetric structure, we focus on slice 2 and slice 15 as examples. We find that the asymmetry of their correlation structures on the away side represents different orientation. For slice 2 as shown in Fig. 2, the height of peak centered at around 2.8 rad is higher than that centered at around 3.8 rad, which is due to that on the away side direction particles travel through longer medium path length at around 3.8 rad (i.e. the left side medium of the back-side of slice 2, namely slice 10) than that at 2.8 rad (i.e. the right side medium of the slice 10). For slice 15, it shows the opposite asymmetry. To guide the eyes, the two Gaussian fits are plotted for the Slice 2 and 15. Consequently, hadrons travel through different medium length and induce different asymmetry of the away-side dihadron structure. In other words, the correlation structure depends on the path-length that the associated particles travel.

Our simulation result seems to indicate that violent parton cascade processes can make significant contributions to the splitting structure in the away-side dihadron correlations. Recent preliminary results by Ma et al.

showed that the double peak structure of final-state dihadron correlation can also be generated when a back jet traverses the dense core due to the shadowing effect of the core [42]. In this picture, the dense core shadowing effect is induced by the transverse expansion or radial flow of colliding system. When partons traverse through a dense core region, they will suffer strong interactions with the medium, which will lead to extensive diffusions and particle redistributions. In the event-averaged case when jet traverses the dense medium, the double peak structure could be due to the sum of deflected and/or cone-like jets. This dense core shadowing effect is also related to path length dependence of jet-medium interactions. The longer path length direction coincides with the direction into the dense core, jet particles are blocked strongly due to the shadowing effect. The asymmetry in the path length distribution for particles interacting with the dense core medium will result in the asymmetry in the dihadron correlation.

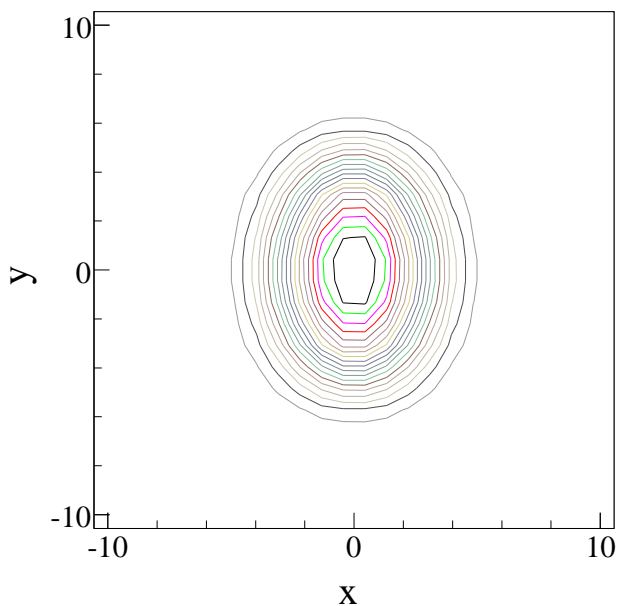


FIG. 1: (Color online) The initial parton distribution in transverse plane from AMPT model simulation of Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV for 40% centrality.

To further investigate the path-length effect, we compared correlation functions from mid-central collisions with central collision results. We show dihadron azimuthal angle correlation functions for 0-10% centrality and 20-60% centrality from AMPT model simulations in Figure 4. We divide the first quadrant of initial phase space region into 6 equal slices based on  $\phi_s$  and in order to increase the statistics, we fold the other three quadrants into the first quadrant. Significant differences in the correlation functions between these two centrality bins become apparent. For mid-central collisions, we observe an evolution from a single peak to double peak structure. But for central collisions, the correlation functions

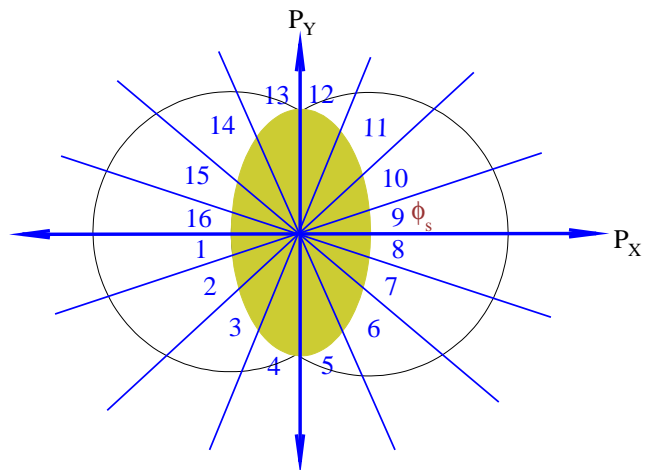


FIG. 2: (Color online) Schematic illustration of 16 slices of trigger particle azimuthal angle relative to the event plane,  $\phi_s = \phi_T - \Psi_{EP}$ .

show little variation with  $\phi_s$  and double peak structure is present for all slices. This can be explained that for central collisions, the overlap region of the two colliding nuclei is almost spherical and the dimensions of the dense medium are such that both in-plane and out-of-plane path length are long enough to generate a splitting structure. We conclude that in order to generate a double peak structure, a dense medium of sufficiently large size is needed [43]. Our simulation results indicate that the onset of the splitting structure corresponds to  $\phi_s \sim 45^\circ$  for 20-60% centrality. The associated particle yields per triggered particle for central collisions is larger than that for mid-central collisions on both near and away side.

In what follows, we will extract a few parameters from the dihadron angular correlation functions to describe the away-side correlation shape and amplitude. Systematic comparisons of these parameters between experimental results and theoretical calculations will provide insight on the response of the medium to the jet energy loss, and may provide new constraints for understanding competing mechanisms for energy transport.

Figure 5 presents the AMPT model calculations of the trigger direction dependence of the away side broadening from Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV. For central collisions, the away-side width  $W_{rms}$  grows very slightly with  $\phi_s$ . For 20-60% central collisions, however, the away-side  $W_{rms}$  grows distinctly with trigger direction  $\phi_s$  which qualitatively agrees well with the experimental measurement [34]. For  $\phi_s$  close to 0 rad, the  $W_{rms}$  for 0-10% Au+Au collisions is already large enough which represents a remarkable broadening of the away-side correlation function, while that for the 20-60% Au+Au collisions is relatively small corresponding to a narrow correlation. This is consistent with expected dependence on the traversing path length in the reaction plane direction between these two centrality bins. For  $\phi_s$  close to  $\pi/2$

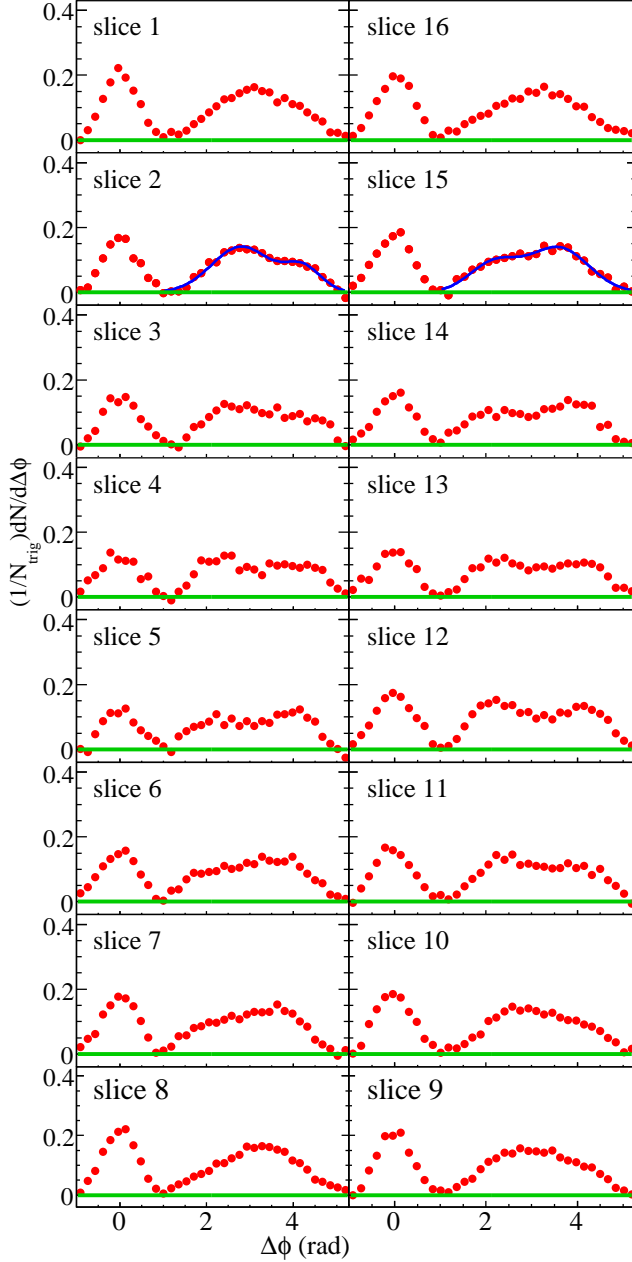


FIG. 3: (Color online) Background subtracted dihadron correlations with trigger particles in 16 slices of azimuthal angle relative to the event plane,  $\phi_s = \phi_T - \Psi_{EP}$ . The data are from the melting AMPT model simulations with hadron rescattering on Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV for 20-60% centrality. ( $p_T$  window cut in model:  $2.5 < p_T^{trig} < 6$  GeV/c and  $0.15 < p_T^{asso} < 3$  GeV/c). Both the trigger and associated particles are restricted within  $|\eta| < 1$ . The solid line in Slice 2 and 15 represents the two-Gaussians fit for the away side dihadron correlation.

rad, the  $W_{rms}$  of these two centrality bins are very much close to each other. This can be attributed to the fact that the path length perpendicular to the reaction plane is not much different between these two centrality bins. The path length variation with the trigger particle orientation in the central collisions is relatively small com-

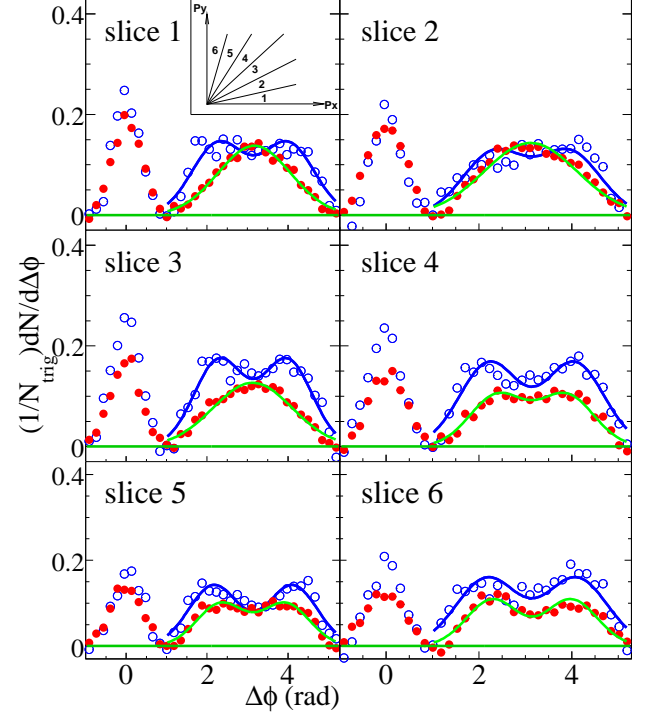


FIG. 4: (Color online) Background subtracted dihadron correlations for trigger particles of  $2.5 < p_T^{trig} < 6$  GeV/c and associated particles of  $0.15 < p_T^{asso} < 3$  GeV/c from AMPT model simulation of Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV with trigger particles in 6 equal slices of azimuthal angle from the event plane in the first quadrant for 0-10% collision centrality (open circles) and 20-60% collision centrality (solid circles). The  $\eta$  window is restricted within  $|\eta| < 1$ . Lines represent the two-Gaussians or one-Gaussian fit for away-side correlation.

pared to that in the mid-central collisions. Accordingly, the away side  $W_{rms}$  for central collisions varies little with  $\phi_s$  and is larger than that for mid-central collisions at all trigger particle orientations.

Figure 6 shows the trigger particle azimuthal angle dependence of the away-side splitting parameter  $D$  (half distance between two splitting peaks on away-side in dihadron azimuthal angle correlation). For mid-central collisions, the splitting parameter  $D$  grows significantly with the trigger particle azimuthal angle while for central collisions it grows only slightly. It can also be attributed to different path-length variations between these two centrality bins. We also show the trigger particle azimuthal angle dependence of correlation yields for both near and away side in Figure 7. On near-side, the yields decrease with trigger azimuthal angle while on away-side, the yields increase.

Figure 8 presents the  $\Delta\phi$  dependence of mean  $p_T$  for in-plane and out-of-plane associate particles. We have combined data of the slices 1, 2, 7, 8, 9, 10, 15 and 16 into in-plane result and the rest into out-of-plane result. On the near-side, the mean  $p_T$  values for both in-plane and out-of-plane agree well with each other and they stay almost constant. On the away-side, they show different an-



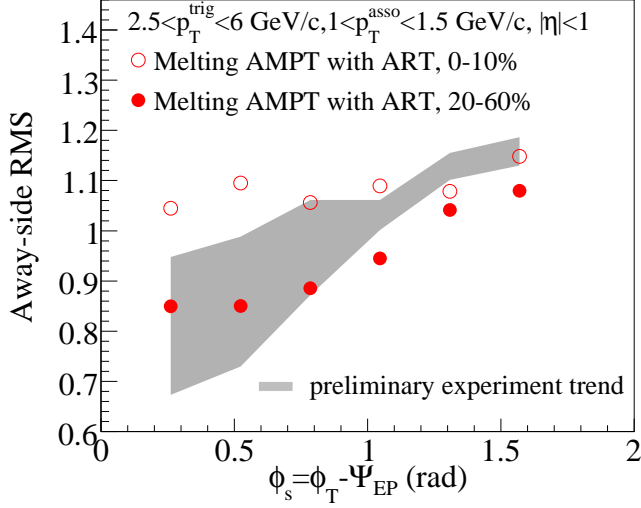


FIG. 5: (Color online) The away-side  $W_{rms}$  of the dihadron correlation function versus the trigger particle azimuthal angle relative to the event plane,  $\phi_s$ , from the AMPT model calculation with  $p_T$  window cut ( $2.5 < p_T^{trig} < 6$  GeV/c and  $1 < p_T^{asso} < 1.5$  GeV/c) in 0-10% (open circles) and 20-60% (solid circles) Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV. The  $\eta$  window is restricted within  $|\eta| < 1$ . The preliminary experimental trend is for 20-60% centrality [34].

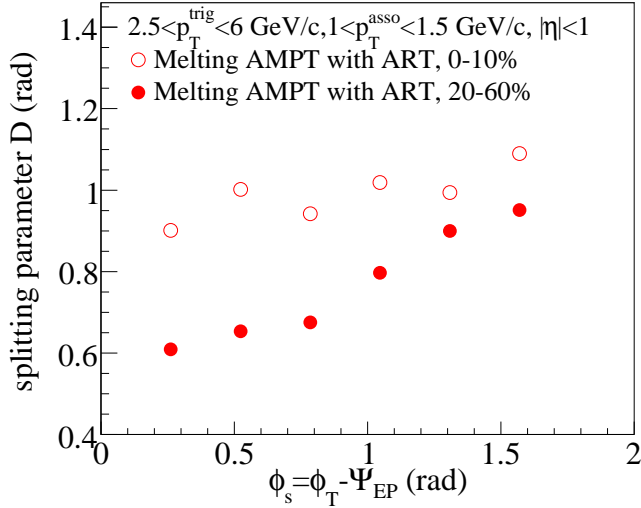


FIG. 6: (Color online) The splitting parameter  $D$  as a function of trigger particle azimuthal angle from the event plane for trigger hadrons of  $2.5 < p_T^{trig} < 6$  GeV/c and associated hadrons of  $1 < p_T^{asso} < 1.5$  GeV/c from AMPT model simulations for Au+Au 0-10% (open circles) and 20-60% (solid circles) collisions at  $\sqrt{s_{NN}} = 200$  GeV.

gular dependence. The mean  $p_T$  for in-plane stays almost flat while for out-of-plane, the mean  $p_T$  displays concave structure with the minimal value at around  $\pi$  rad. Previously published results indicate that for central collisions the concave structure implies that harder associated hadrons prefer larger angles with respect to the back-to-back direction and it may be attributed to the average interaction length of the away-side partons interacting with the medium is maximal at  $\Delta\phi = \pi$  rad [44]. Our results indicate that for mid-central collisions, the path-

length on away-side for in-plane is relatively small, and it varies very little with  $\Delta\phi$ . For out-of-plane, however, partons on the away-side direction will travel through a long enough path length in the medium leading to a significant energy loss; partons emitted away from the back-to-back direction will traverse through relatively smaller path length with a correspondingly smaller energy loss. The path-length effect plays an important role on the structure of mean  $p_T$  for the away side particles.

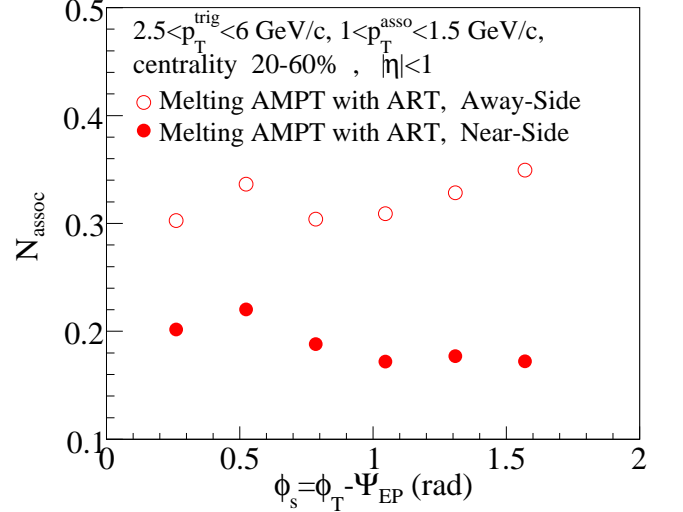


FIG. 7: (Color online) The yields of the dihadron correlation function on near (solid circles) and away side (open circles) versus the trigger particle azimuthal angle from the event plane,  $\phi_s$ , with  $p_T$  window cut ( $2.5 < p_T^{trig} < 6$  GeV/c and  $1 < p_T^{asso} < 1.5$  GeV/c) in 20-60% Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV. The  $\eta$  window is restricted within  $|\eta| < 1$ .

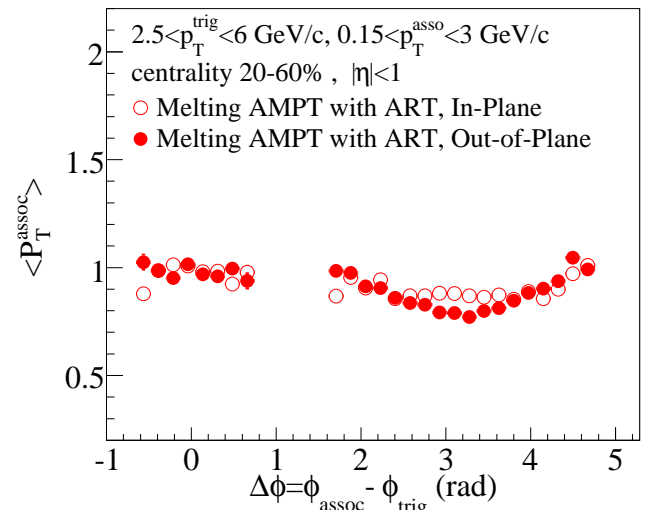


FIG. 8: (Color online) The mean  $p_T^{asso}$  versus  $\Delta\phi$  ( $\phi_{assoc} - \phi_{trig}$ ) for in- (open circles) and out-of-plane (solid circles) dihadron  $\Delta\phi$  correlations with  $p_T$  window cut ( $2.5 < p_T^{trig} < 6$  GeV/c and  $0.15 < p_T^{asso} < 3$  GeV/c) in Au+Au collisions (20-60%) at  $\sqrt{s_{NN}} = 200$  GeV. The  $\eta$  window is restricted within  $|\eta| < 1$ .

#### IV. CONCLUSIONS

In conclusion, dihadron azimuthal angle correlation functions with respect to reaction plane have been studied in the framework of a hybrid dynamical transport model, namely the AMPT model. In this model, the energy loss is essentially from elastic parton-parton scattering process, and the gluon radiation energy loss mechanism has not been included yet. In order to match the experimental observations, a large elastic cross section has to be used. With the AMPT model simulations we observed the emerging of the splitting structure in the away-side dihadron correlations from Au+Au collisions at 200GeV/c. We found that the structure in the azimuthal angle correlation functions has a strong dependence on the trigger particle orientation relative to the reaction plane, which is consistent with the observation from the STAR experiment. The correlation amplitude on the near-side slightly decrease from the in-plane to the out-of-plane direction, while the shapes of the away-side angular correlation functions evolve from a single peak to double peaks. For the triggered particles emitting from middle azimuthal angles relative to the reaction plane, the corresponding away-side correlation function is asymmetric which indicates that the shape of the correlation shall be sensitive to the traversing path length. By comparing results in the top 0-10% and 20-60% collision centrality bins, we found that the away-side path length in the reaction plane direction in 20-60% Au+Au collision was not long enough to generate a double peak structure while that in the top 0-10% collision it was long enough to do that. While in the out-of-plane direction, the correlation structure seems to be not very different since the path length is similar between these two centrality bins along this direction. We extracted a few parameters from correlation functions and discussed the possible underlying mechanisms for the splitting structure. Our results indicate that the away-side  $W_{rms}$  and splitting parameter  $D$  increase with  $\phi_s$  for 20-60% centrality while for 0-10% centrality they change very slightly. This observation underscores the importance of the path-length effect when

the away-side associated particles traverse the medium. The yields on near-side decrease slightly with  $\phi_s$  while on the away-side they increase. We also investigate the  $\Delta\phi$  dependence of associated particles mean  $p_T$ . The dip structure of mean  $p_T$  as a function of  $\Delta\phi$  along the out-of-plane direction is more prominent than that along the in-plane direction. These results could shed light on path-length effect of elastic collision energy loss for high transverse momentum particles propagating through the hot and dense medium. Strong parton cascade processes and resultant energy loss play important roles in the interaction between the jet-like particles and medium in the AMPT model. Furthermore, the preferential way to reconstruct the reaction plane in experiment now is using the  $m$ -th harmonic plane, of which the second harmonic plane, i.e.,  $v_2$ -method, is often used [34]. If one uses the first harmonic plane ( $v_1$  method), it will be possible to distinguish between structures of different trigger particle emission regions, thus allowing to separate different path length effect in experiment. We note that the present findings are mostly relevant for the elastic energy loss and we do not know contributions from gluon radiation loss and their consequence on dihadron correlations yet in a dynamical model simulation. Nevertheless, our studies indicate that path length effect in jet medium interactions is very important and should be thoroughly investigated both experimentally and theoretically.

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